EOPACE (Electrooptical Propagation Assessment in Coastal Environments) Overview and Initial Accomplishments

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SUMMARY
EOPACE is a five year international experiment to improve performance assessment for electrooptical systems operating in coastal environments. Initial -results concern coastal aerosols. Aerosol optical depths in the marine atmospheric boundary layer derived from satellite images compare well with those measured directly inside the layer. Analysis of mid wave infrared transmission at low altitude above San Diego Bay shows a constant (30%) attenuation due to molecules and a variable (0% to 70%) attenuation due to aerosols and refractive focusing effects. Extinction coefficients derived from aerosol particle size distributions measured in the air above breaking surf show that aerosol extinction increases by an order of magnitude as the ocean surface is approached from a height of 8 meters.

LIST OF SYMBOLS
L Range (km).
m Subscript referring to molecules.
N Particles per unit volume (cm-3).
p Subscript referring to particles.
Q Mie efficiency factor.
r Particle radius (microns).
x Position or distance (km).
T Optical depth.

β_p Aerosol extinction coefficient (km-').
λ Wavelength (microns).
τ Measured transmission (%).
τ_m Molecular transmission (%).
τ_p Aerosol transmission (%).

1. EOPACE OVERVIEW

EOPACE is a measurement and analysis program to improve performance assessment for electrooptic weapon and sensor systems operating in coastal environments [1]. The measurement campaign, which began in January, 1996, is being conducted in the California coastal region by participants from NATO countries. Coastal conditions may differ significantly from those in the open ocean and have not yet been fully characterized. The climate of the California region is similar to that of other interesting regions, such as the Mediterranean Sea, and represents an excellent example of a littoral environment.

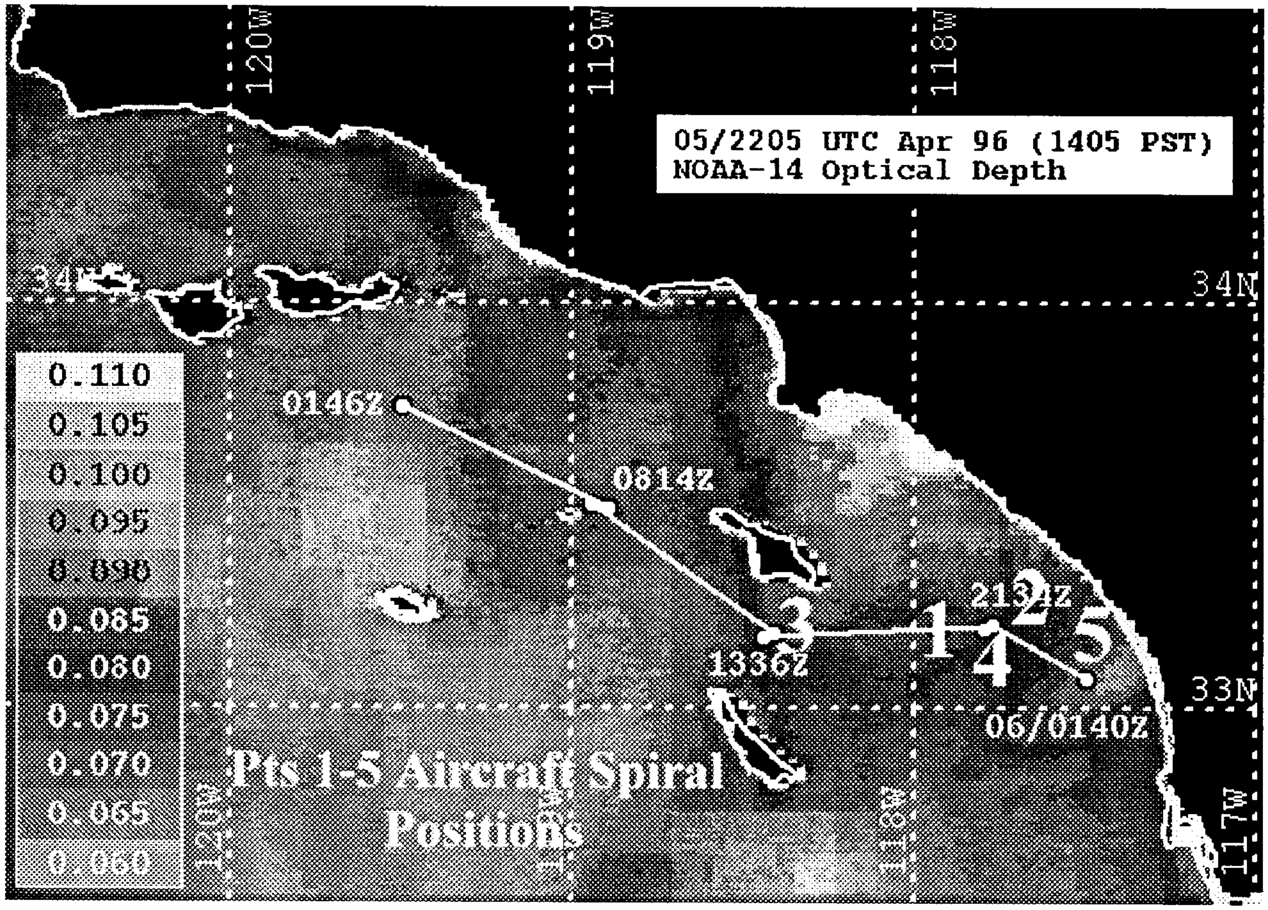
The specific objectives of EOPACE are: (1) to assist in the development of mesoscale and data assimilation models, (2) to evaluate the performance of EO systems in coastal regions, and (3) to investigate coastal aerosols.

The key feature of EOPACE[1] is its long observation period, one to two years, interspersed with several intensive operational periods lasting two to three weeks each. Long term observations increase the chance of encountering a full range of atmospheric conditions. EOPACE will provide the database for mesoscale model development and evaluation. The performance of EO systems will be evaluated from measurements and studies of targets and backgrounds, polarization effects, IRST and FLIR performance, and tactical decision aids. For the coastal aerosol study, measurements will support the investigation of surf production of aerosols, characterization of coastal air masses, and characterization of near ocean surface transmission.

2. COASTAL AIR MASSES.

The goals of the air mass characterization effort are: (1) to provide a database for initializing and testing the mesoscale coastal aerosol models currently under development, (2) to determine if the air mass parameters in various coastal locations can be derived from remotely sensed satellite imagery, (3) to evaluate the optimum satellite-derived air mass parameters for Navy real-time assessment and dynamic aerosols models, and (4) to establish the variability of aerosol concentration and composition for coastal air masses.

[1] Further information is available on the intemet at http://sunspot. nosc.mil//543/eopace/eomain.html.



Figurel. Aerosol optical depth in the marine atmospheric boundary layer off the coast of Southern California inferred from visible and near infrared data provided by the NOAA AVHRR satellite. The large numerals, 1 thorugh 5, refer to the location of a Piper Navajo aircraft which carried equipment capable of directly measuring the aerosol size distribution within the boundary layer. The white line is the track of the research vessel Point Sur which carried similar instruments. The Point Sur measurements are not discussed in this paper.

Figure 1 shows the coast of California, stretching from San Diego in the lower right hand comer through the Los Angeles basin to Santa Barbara in the upper left hand comer. Land regions are blacked out. Also shown in black are islands off the California coast. The shading superimposed on the water of the California bight represents the aerosol optical depth

$$T_\lambda(L) = \int_0^L \beta_p(x,\lambda)\, dx \qquad (1)$$

whose values are given in the inset on the left hand side of the figure. The aerosol optical depth was derived from radiometric measurements transmitted by the NOAA AVHRR satellite on 5 April, 1996, at 2205 GMT. The analysis follows the Durkee retrieval technique [2, 3] applied to satellite channels 1 (visible) and 3 (mid wave infrared). The technique rests [4] on three assumptions: (1) that the boundary layer is well mixed, (2) that optical depth is completely determined by aerosol extinction, and (3) that the amount of water vapor in the boundary layer is known by other techniques. The optical depths shown in figure 1 do not include molecular absorption, but they do include aerosol scattering in the troposphere and the marine atmospheric boundary layer. It is assumed that aerosols in the -- marine boundary layer provide the major contribution to these data.

On the same day, a twin engine Piper Navajo aircraft carrying a forward scattering spectrometer probe [5] executed vertical spiral patterns at locations given by the large numerals in figure 1. The probe measures the aerosol particle size distribution *dN/dr*. From

Table 1
Aerosol Optical Depth

Location	Aircraft	Satellite
1	0.073	0.075
2	0.052	0.085
3	0.063	0.085
4	0.056	0.075
5	0.072	0.090

these data the extinction was calculated from Mie theory [6] using

$$\beta_p(x,\lambda) = \int_0^\infty \pi r^2 Q_p(x,\lambda)\frac{dN}{dr}dr \qquad (2)$$

along with equation (l).

Table 1 compares satellite depths with aircraft depths. In all cases the aerosol depth measured by the aircraft inside the boundary layer is close to, but slightly less than, the satellite derived optical depth. This is to be expected if tropospheric aerosols represent the small excess of satellite over aircraft optical depths.

3. LOW ALTITUDE TRANSMISSION.
The goal of the near ocean surface transmission characterization is to quantify infrared propagation characteristics for the mid wave (3-5 micron) and long wave (8-12 micron) bands for transmission close to the surface of the ocean, and to determine the measurable meteorological parameters near the ocean surface by which IR transmission may be estimated.

Continuous mid wave infrared transmission has been measured close to (several meters above) the ocean surface over a two week period. The transmission range [1] extended 6998 m from a transmitter located at Coronado, California, to a receiver located at Point Loma, California, on a bearing of 255.9° true. The transmitter consisted of a 1000 K glower placed in the focal plane of a 20 cm diameter F/6 paraboloidal mirror coated with aluminum. The source was chopped at 960 Hz. The transmitter was mounted 3.41 m above mean sea level on the stable platform shown in figure 2. The receiver consisted of a 3 mm square InSb detector placed in the focal plane of an identical mirror at an altitude of 3.04 m above mean sea level. A room temperature optical filter with a pass band of 3.4 to 4.0 microns was placed in front of the detector. The mid wave signal was detected by a lock-in amplifier which received a reference signal transmitted from the source by a radio operating at 160.1 MHz.

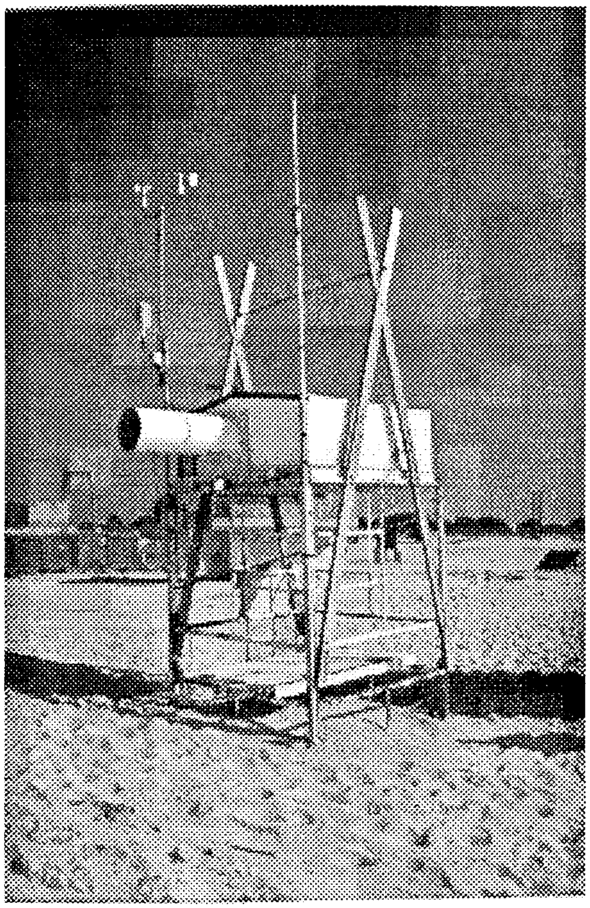


Figure 2. The transmitter located at the Naval Amphibious Base at Coronado.

Prior to field deployment, the equipment was calibrated in the laboratory with the same settings as those used in the field. By correcting the laboratory signal for inverse square law fall-off, a full range free space[2] signal of 6.32 ± 1.90 mV was obtained. In the field the time constant of the lock-in was 1 s with a roll-off of 12 dB/octave and the average of 6 consecutive readings, each separated by 10 s, was reeorded every minute in a computer. With these

[2] By "free space" we mean what would loosely be thought of as "1OO'%O transmission". The correction assumes a source underfilling the detector field of view at full range, no atmospheric absorption, no refractive ray bending, and no refractive focusing.

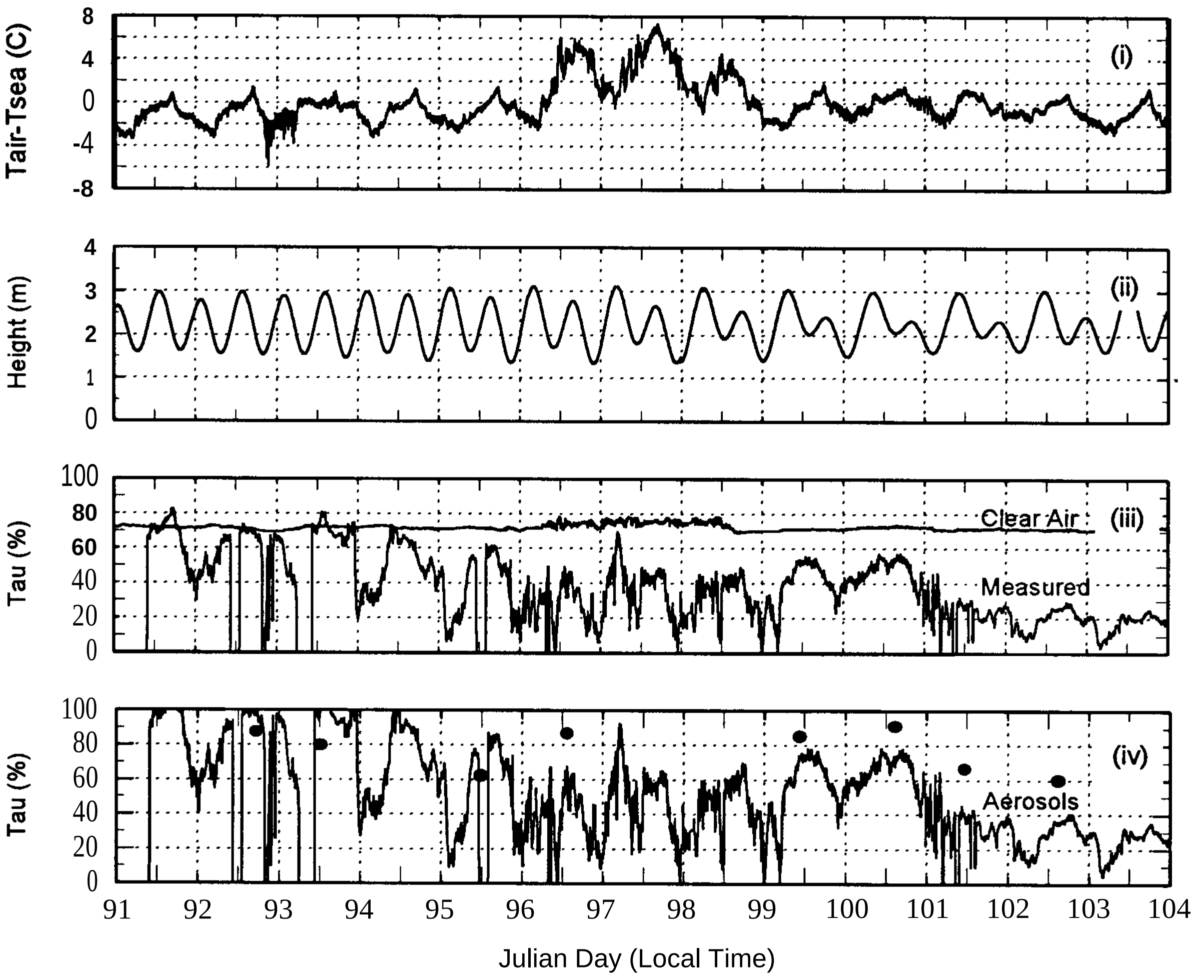


Figure 3. Meteorological and transmission data measured along a 7 km path across San Diego Bay during 13 days in April 1996. (i) Difference between air and sea temperatures measured at the mid path buoy. (ii) Altitude of optical path above the ocean surface at the mid path buoy assuming no refraction (i. e., a straight line path between transmitter and receiver). (iii) Lower curve: measured mid wave infrared transmission. Upper curve: clear air (molecular) transmission predicted by MODTRAN2 from the temperature and relative humidity at the mid path buoy. (iv) Curve: ratio of results in figure (iii). Solid circles: aerosol transmission inferred from particle size distribution measured from a small boat traversing the 7 km path.

settings, the detector noise was 3 μV (0.05 % of free space). The sensitivity of the system in the field was limited by turbulent fluctuations of the signal which were observed to be on the order of 0.6 mV (10’Yo of free space).

Transmission and meteorological data from this experiment are shown in figure 3 for a 13 day period in April 1996. The uppermost curve is the difference between air and sea temperatures at a buoy located in San Diego Bay at the middle of the transmission path. The sea temperature remained almost constant, so this curve reflects normal diurnal temperature variations in a coastal region. The increased amplitude in the middle of this curve resulted from a Santa Ana weather condition which took place on days 96, 97, and 98. The next curve, figure 3 (ii), is the height of the optical signal above the ocean at mid path assuming free space conditions, i.e., a straight line path between transmitter and receiver. The height variation is due to the tide. Transmission measurements for the mid wave infrared band are shown by the lower curve[3] in part (iii) of figure 3.

[3] Sections of the this curve which change abruptly to zero, for example at day 92.5, are artifacts due to the detector running out of liquid nitrogen.

The upper curve in part (iii) is the clear air[4] transmission that would be expected under the conditions of pressure, temperature, and relative humidity observed each minute at the mid path buoy. Those times when the measurements exceed the clear air result can be explained either by the absolute accuracy of the measurement@ 30%) or the presence of refractive focusing effects. Molecular effects were removed by applying the left hand equality of

$$\tau_p = \frac{\tau}{\tau_m} \approx \exp\{-\beta_p(\lambda) \cdot L\} \qquad (3)$$

to the measured data, resulting in the curve shown in part (iv) of figure 3.

The solid circles in figure 3 (iv) represent the transmission that would be expected on the basis of aerosol effects alone. These data were measured by transporting a forward scattering spectrometer probe [5] in a small boat inbound (that is, from the transmitter to the receiver) along the over-water portion of the 7 km range. The inbound trip took about 30 minutes, and the aerosol size distribution was integrated for the entire inbound paths. A representative inbound spectrum is shown in figure 4. Applying equations (2) and (1) to data[6] such as those shown in figure 4 for a wavelength of 3.5 microns resulted in the solid circles shown in figure 3 (iv).

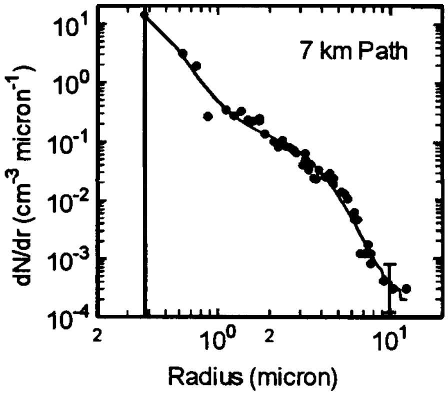


Figure 4. **Aerosol size distribution measured inbound on the 7 km transmission path on April 8, 1996. The solid line is** a **fifth order polynomial fit to the data from which the mid wave extinction coefficient was derived using Mie theory.**

The transmission data shown in figure 3 deserve two comments. **First,** the molecular transmission remained remarkably constant: the mean value was 72% and the standard deviation was 1.6% during the entire 13 day period. This is no doubt due to the fact that the molecular transmission depends on the specific humidity, the number grams of water vapor per unit volume of the atmosphere, and the specific humidity remains relatively constant in spite of wide variations in air temperature and relative humidity from one day to the next. Second, the measured transmission can be successfully explained by molecular and aerosol effects because of the agreement (within the experimental error) between the solid circles and the curve in figure 3 (iv). Nevertheless, we must warn that refractive focusing and mirages will contribute substantially to any signal such as this one, observed at low altitudes over land or sea, and such contributions have yet to be analyzed for these data.

We close this section by noting that, in comparing the aerosol data from the boat with the transmission - data, we have made use of Beer's Law, the right hand equality of equation (3). Beer's Law holds for aerosols because of their smooth spectral behavior, but it does not hold either for the measured transmission, the numerator of equation (3), or the molecular transmission, the denominator of equation (3), because of their rapidly varying spectral

[4] By "clear air" is meant the transmission due solely to molecular absorption and scattering with no aerosol or refractive focusing effects taken into account. This curve was calculated using MODTRAN2 without the subroutine "Fudge", a procedure whose result, for a single typical value of temperature and relative humidity, was within 2% of the MODTRAN3 calculation.

[5] Outbound data were taken but not used because they were compromised by the prevailing wind, which tended to blow aerosols from the diesel exhaust toward the bow of the boat where the aerosol spectrometer was mounted.

[6] The integral in equation (2) was truncated at a radius of 0.4 μm, the smallest radius for which data were available. The neglected particles of smaller radius, while undoubtedly present to some degree given the observed visibility of 15 km, are not so numerous as to substantially alter the extinction at 3.5 μm because of their small size with respect to that wavelength.

behavior'. Hence, of the transmission results shown here, only the aerosol data can be extrapolated to other ranges; the clear air and measured data cannot.

4. SURF PRODUCTION OF AEROSOLS

The goals of the aerosol surf production effort are (1) to determine the impact of surf-generated aerosols on visual and infrared extinction in coastal environments, and (2) to evaluate the measurable meteorological and physical oceanographic parameters of a surf zone by which surf aerosol production may be estimated.

The role of surf generated aerosols has been 'investigated by measuring aerosol size distributions in the atmosphere close (several meters) above breaking waves. A forward scattering spectrometer probe [5] was again used to measure the aerosol size distribution this time by being placed in a box which was suspended from the pier at the Scripps Institute

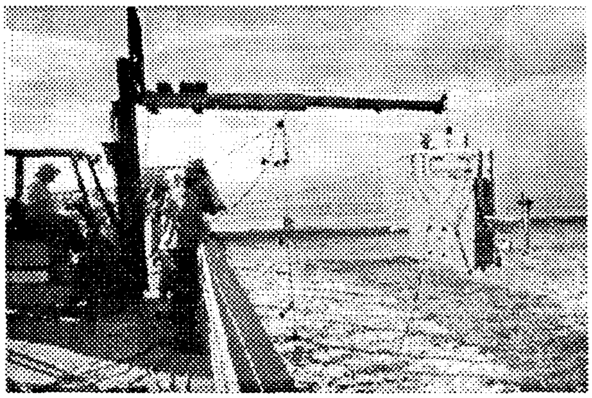


Figure 5. The instrumented box could be suspended at varying heights above the surf for aerosol and supporting meteorological measurements.

of Oceanography at fixed heights above the ocean surface. Figure 5 is a photograph of the box, which atso contained aerosol rotorods and standard meteorological instruments for measuring temperature, wind speed, and relative humidity. Typical integration times spent at each height were 30 minutes, resulting in particle size distributions similar to that shown in figure 4. Following the procedure involving equations (1) and (2) which has already been described, the extinction coefficient at four[8] different optical wavelengths shown in figure 6 were derived. The spectral dependence of these curves, which always show a maximum at 3.5 μm, is consistent with supplemental data, not included here, showing that the concentration of surf aerosols reached a peak for radii between 1 and 10 μm and so would be most influential near 3.5 pm. The height dependence of these curves show that, as the breaking waves on the surface of the ocean are approached from the initial altitude of 8 m, the visible and infrared extinction increase by almost an order of magnitude. Since aerosol transmission follows Beer's Law and thus depends exponentially on extinction, these data demonstrate a large influence of surf aerosols on electrooptic systems in

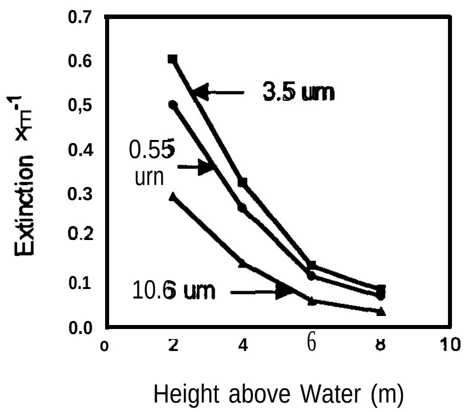


Figure 6. Extinction coefficient at three optical wavelengths as a function of altitude above the ocean surface.

coastal environments.

5. CONCLUSION

Electrooptical systems operating in coastal environments are subject to varied and complex atmospheric conditions which can change rapidly. EOPOACE is a five year field experiment designed to gather information about the coastal environment in the Southern California bight. Initial results concern coastal aerosols. Satellite data on aerosol optical depth in the marine atmospheric boundary layer have been correlated with airborne aerosol size

[7] The spectral integral of a rapidly varying spectrum does not obey Beer's Law, even though it might be obeyed at each wavelength in that spectrum, for the same reason that the sum of two different exponential is not equivalent to a single exponential.

[8] The data at 1.06 μm overlapped the data at 0.55 μm to within the experimental error and have been removed from the figure for clarity.

distributions measured at the same time directly within the boundary layer. Mid wave infrared transmission measurements made along a 7 km path several meters above the surface of San Diego Bay are consistent with the hypothesis that aerosols and molecules determine the transmission behavior. Aerosol size distributions at fixed altitudes close above breaking surf predict an order of magnitude increase in optical extinction as the ocean surface is approached.

EOPACE PARTICIPANTS

From the United States, participating organizations include the Office of Naval Research (ONR) in 'Washington D. C.; the Naval Command, Control and Ocean Surveillance Center, RDT&E Division (NRaD) in San Diego, California; the Naval Research Laboratories in Monterey, California and in Washington, D. C.; the Naval Air Warfare Center at Pt. Mugu, California; the Applied Research Laboratory at Pennsylvania State University; California State University at Long Beach; the Naval Postgraduate School in Monterey, California, the Naval Surface Warfare Center in Silver Springs, Maryland; and the California Air Resources Board.

Foreign participants include the Physics and Electronics Laboratory TNO from The Netherlands; the University of Manchester Institute of Science and Technology (UMIST) in the United Kingdom; the Defense Research Establishment Valcartier in Quebec, Canada; and the Australian Defence Science and Technology Organization, Adelaide/University of Western Australia in Perth, Australia.

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